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This report combines independent studies carried out by Vincent Nelson and Victor Church. Nelson's study covered the western end of the Gros Ventre Mountains and the northwestern end of the Hoback Range, while Church's area included the central Gros Ventres and the northeastern end of the Hoback Range. In order to present a more comprehensive report and eliminate undesirable repetition it was thought advisable to combine the results in a joint paper.

A DISSERTATION SUBMITTED TO THE FACULTY  
OF THE DIVISION OF THE PHYSICAL SCIENCES  
IN CANDIDACY FOR THE DEGREE OF DOCTOR  
OF PHILOSOPHY

DEPARTMENT OF GEOLOGY AND PALEONTOLOGY

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## CRITICAL STRUCTURES OF THE GROS VENTRE AND NORTHERN HOBACK RANGES, WYOMING

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### ABSTRACT

The Rocky Mountain geosyncline had an irregular development, so that locally there were basin-like areas where pre-Laramide sediments accumulated in greater thicknesses than elsewhere. This marked difference in total thicknesses of Paleozoic and Mesozoic sediments gave rise to two distinct types of structural development in the Middle Rocky Mountain province, namely, foreland and geosynclinal. The area discussed in this report is particularly significant from the standpoint of the mechanics and sequence of development of these structural types, for only at the southern end of the Teton Range and at the junction of the Gros Ventre and Hoback ranges are pronounced structures of the two types in juxtaposition. The structures of the western and central Gros Ventres are described and shown to be typical of a foreland area, while the northern end of the Hoback Range displays structures typical of a geosynclinal tract. Laramide deformation in this border zone occurred in two stages, with the Gros Ventres (foreland area) yielding first and serving as a buttress against which the structures of the geosynclinal tract were crowded. A period of Tertiary high-angle faulting is also recorded, together with comparatively recent epeirogenic movements.

### INTRODUCTION

This report is based on field work carried out by the writers during portions of the summers of 1937, 1938, and 1939. Mapping for the study covers an area of approximately 240 square miles, lying within the Jackson and Gros Ventre quadrangles of northwestern Wyoming. It includes the central and western portions of the Gros Ventre Range and the northern end of the Hoback Mountains.

The Gros Ventre Mountains constitute one of the more or less detached ranges of the west-central portion of the Middle Rocky Mountain province. They are a relatively small unit, being but 40 miles

long and from 15 to 20 miles wide and trending northwest southeast. The western termination of the range is quite abrupt, forming a part of the eastern rim of Jackson Hole, but at its eastern extremity a gentle dip slope leads down into the valley of Green River, where the beds reverse their dip to rise in the western flank of the Wind River Range. The northern boundary of the Gros Ventre Range is ill defined but has been arbitrarily placed at the Gros Ventre River. A well-defined topographic boundary exists along the south side of the range from its eastern termination to a point approximately 27 miles to the northwest,

but here the Gros Ventre and Hoback ranges join, making a separation on the basis of topography difficult. Here the boundary is better determined on the basis of structure. Most of the high peaks of the Gros Ventre Range reach elevations of approximately 11,000 feet.

The Hoback Range is a narrow, linear unit extending southward from the Gros Ventre Mountains for about 30 miles. It

used by Leland Horberg<sup>1</sup> in mapping the Teton Pass area to the west across Jackson Hole. The section as set forth in Figure 2 is a composite one, utilizing some of the formational names established by workers in the southeastern Idaho-southwestern Wyoming area, as well as some in use in northwestern Wyoming. The necessity of using such a composite section will be readily seen upon exami-

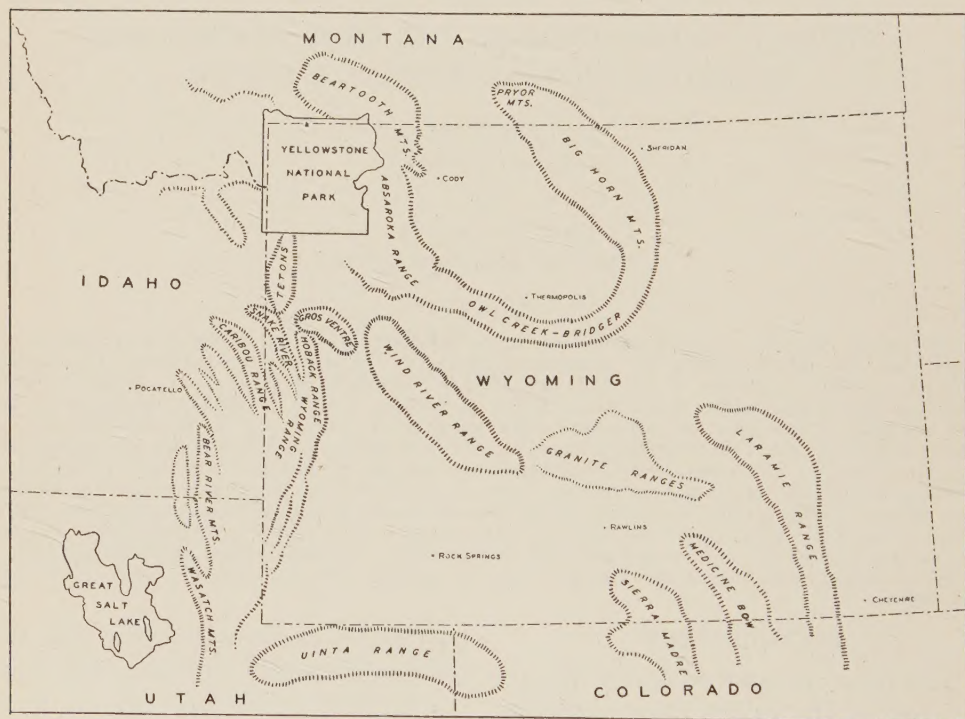


FIG. 1.—Index map

varies in width from but 4 to 6 miles. The peaks at its northern end have an average height of about 10,000 feet, but south of Hoback Canyon the range rises gradually, with Hoback Peak (10,818 feet) the culminating point.

### STRATIGRAPHY

The stratigraphic units used in mapping the area under discussion are listed in the chart (Fig. 2). Except for slight modification, they are the same as those

nation of the isopach map (Fig. 3) of portions of Wyoming, Idaho, and Utah. This map shows that the Rocky Mountain geosyncline had an irregular development. Locally there were basin-like areas where the pre-Laramide sediments accumulated in greater thicknesses than elsewhere. One such basin, or localized area of thick accumulation, centered

<sup>1</sup> "The Structural Geology and Physiography of the Teton Pass Area, Wyoming," *Augustana Library Pub.* 16 (1938).



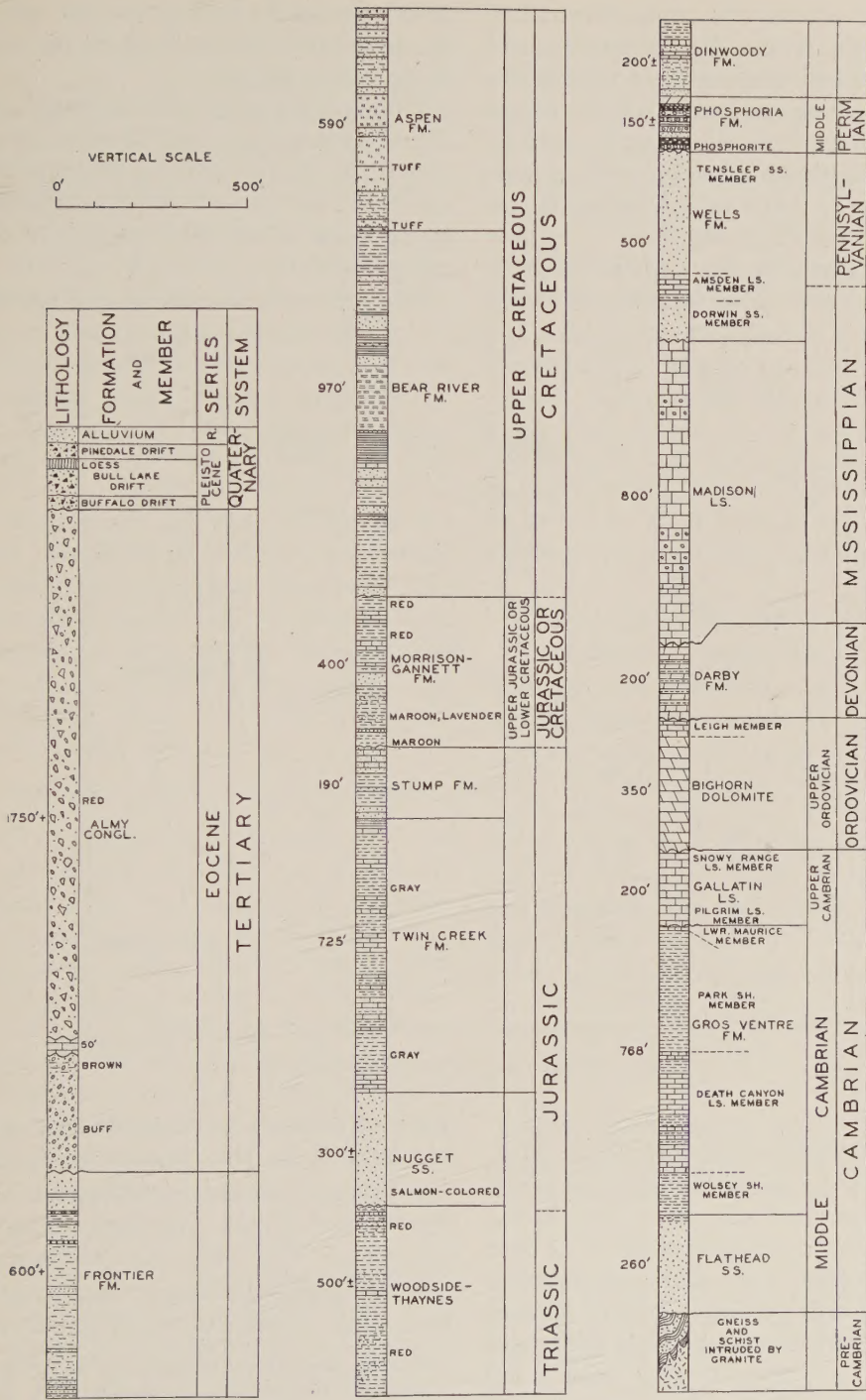


FIG. 2.—Stratigraphic chart

around the corner of Idaho, Wyoming, and Utah, where the Paleozoic and Mesozoic sediments attain a total thickness of over 43,000 feet. To the east and northeast the beds thin rapidly, indicating the existence of a foreland or platform area in that vicinity during the development of the geosyncline.

The Gros Ventre-northern Hoback area is located on the boundary between

thicknesses of the beds of that age within the geosyncline proper than do the beds of the earlier periods.

Numerous stratigraphic problems exist in this boundary area, but the writers were primarily interested in the structural relationships, and therefore established formational names were applied to the mappable units.

The greatest difficulty in utilizing al-

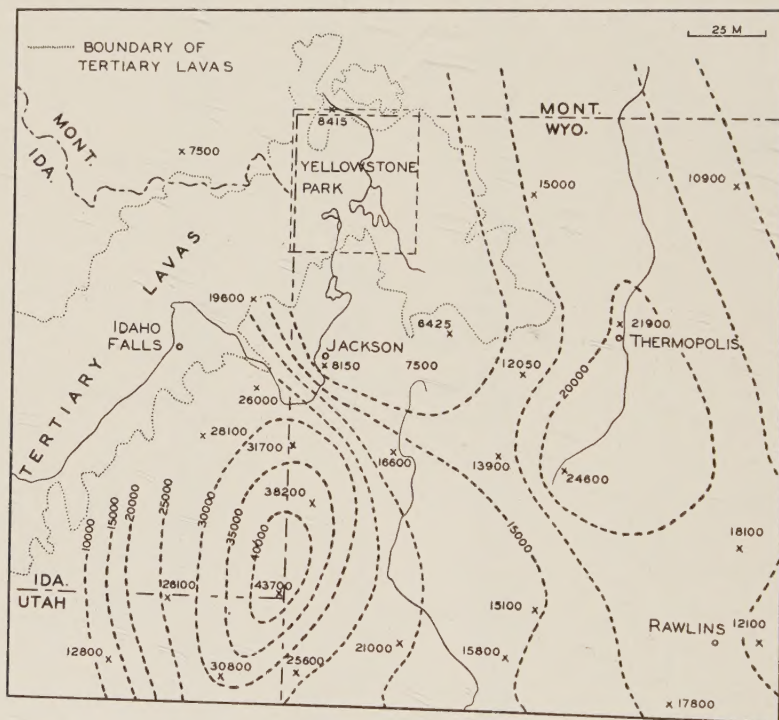


FIG. 3.—Isopach map (after Leland Horberg)

the foreland and geosynclinal tracts or in a region where most formations thicken rapidly to the southwest and pinch out to the northeast. However, in the later stages of its development or near the beginning of the Laramide orogeny the geosyncline enlarged greatly, spreading east and northeast. Thus the Upper Cretaceous sediments well within the foreland tract approach more closely the

ready established formational names was encountered in the Triassic sequence. The Triassic beds are here referred to the Dinwoody and the Woodside-Thaynes formations. The Dinwoody was named by Eliot Blackwelder<sup>2</sup> from the canyon of Dinwoody Lakes in the Wind River

<sup>2</sup> "New Geological Formations in Western Wyoming," *Jour. Wash. Acad. Sci.*, Vol. VIII (1915), p. 425.



Range. Regarding its equivalents to the south and west, he stated:

Westward it becomes progressively thicker, more calcareous, and more fossiliferous, and changes by imperceptible gradations horizontally into the Woodside and Thaynes formations of southeastern Idaho.

But more recent studies of the Triassic of western Wyoming by Norman D. Newell and Bernhard Kummel<sup>3</sup> have shown that the Dinwoody is the equivalent of only the lower portion of the Woodside of southeastern Idaho. While the mapping for this report was being done, the term "Ankareh" was used for the remaining Triassic above the Dinwoody. Newell and Kummel have found that this sequence of beds is equivalent faunally to the upper Woodside and Thaynes formations of southeastern Idaho. Therefore it now seems best to rename the beds that were once called "Ankareh" the "Woodside-Thaynes," using the hyphenated term.

#### REGIONAL TECTONIC SETTING

The controlling structures of the ranges in the Middle Rocky Mountain province in Wyoming, eastern Idaho, southern Montana, and northern Utah may be grouped readily into two distinct classes: foreland and geosynclinal.<sup>4</sup> The broad area in which the foreland structures are characteristic lies to the east of a narrower and more elongate belt of geosynclinal structures (see index map, Fig. 1). It should be noted that the

<sup>3</sup> "Lower Eo-Triassic Stratigraphy, Western Wyoming and Southeastern Idaho," *Bull. Geol. Soc. Amer.*, Vol. LIII (1942), pp. 937-96.

<sup>4</sup> The concept of the two distinct types of structures, namely, foreland and geosynclinal, with reference to the Rocky Mountains has been developed by Dr. R. T. Chamberlin over a number of years in his classes and in field work in this region, making it impossible to cite an original reference in the literature.

pronounced structures of the foreland and geosynclinal areas do not approach one another closely except at the southern end of the Teton Range and at the junction of the Gros Ventre and Hoback ranges. These areas, therefore, are particularly significant, since the juxtaposition of these two fundamental types of structures should throw additional light on the mechanics of their formation and yield further information concerning the Laramide Revolution. Horberg has already described the structures of the Teton Pass area at the southern end of the Teton Range,<sup>5</sup> and a summary of the major structural types and trends of the larger Teton-Gros Ventre-Hoback area has been prepared in manuscript form.<sup>6</sup>

#### FORELAND STRUCTURAL TYPES

The foreland, or platform, structural types include high-angle faults (either normal or reverse), monoclinical flexures, domelike upwarps, and broad, open asymmetrical folds. These developed in response to stresses acting on regions in which the cover of Paleozoic and Mesozoic sediments was relatively thin (20,000 feet or less; see isopach map, Fig. 3). In such areas the structures of the underlying pre-Cambrian crystalline rocks have played the dominant role in determining the nature of the yielding to Laramide stresses.<sup>7</sup> Thus the general

<sup>5</sup> *Op. cit.*

<sup>6</sup> Leland Horberg, Vincent Nelson, and Victor Church, "Structural Types and Trends in Western Wyoming" (unpublished manuscript).

<sup>7</sup> W. T. Thom, Jr., "The Relation of Deep-seated Faults to the Surface Structures of Central Montana," *Bull. Amer. Assoc. Pet. Geol.*, Vol. VII (1923), pp. 1-13; Ernst and Hans Cloos, "Pre-Cambrian Structure of the Beartooth, the Bighorn and the Black Hills Uplifts, and Its Coincidence with Tertiary Uplifting," *Proc. Geol. Soc. Amer.*, 1933 (1934), p. 56; E. C. H. Lammers, "Pre-Cambrian Control of Laramide Structures in the Beartooth Range, Mon-

pattern of the platform region consists of a series of blocklike uplifts, many of which are distinctly rectangular in outline. The larger blocks or ranges are commonly composite in character, in that they usually consist of several small-

ranges) is in the direction opposite from that of the adjoining segment on either side. The reversal of direction of structural asymmetry is one of the outstanding peculiarities of the tectonic development.<sup>8</sup>

The portion of Middle Rocky Mountain province of southern Montana,

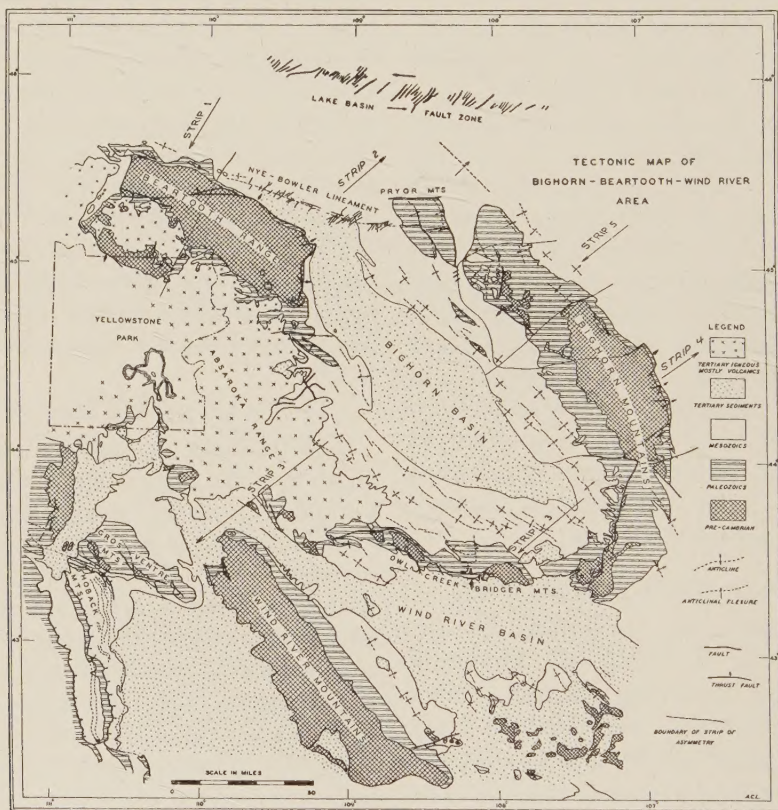


FIG. 4.—Regional tectonic map of Bighorn-Beartooth-Wind River area (after R. T. Chamberlin)

er blocks. With regard to such smaller blocks R. T. Chamberlin states:

Some of the larger of these mountain units consist of subunits, or segments, each of which deformed with a certain individuality of its own. Characteristic of this individuality is a one-direction asymmetry of structural features which persists throughout each individual segment, but (in both the Beartooth and Bighorn

western Wyoming, and northeastern Utah which belongs to the foreland area includes the Pryor-Bighorn, Owl Creek-Bridger, Absaroka-Washaki, Beartooth, Teton, Gros Ventre, Wind River, and Uinta ranges. They all display clear-cut foreland structures, with the exception of the Teton Range, whose major features have resulted from Tertiary faulting. Two distinct groups of tectonic features

tana and Wyoming," *Bull. Geol. Soc. Amer.*, Vol. L (1939), p. 1918; D. L. Blackstone, Jr., "Structure of the Pryor Mountains, Montana," *Jour. Geol.*, Vol. XLVIII (1940), p. 606.

<sup>8</sup> "Diastrophic Behavior around the Bighorn Basin," *Jour. Geol.*, Vol. XLVIII (1940), p. 678.



are noted: (1) the dominating and controlling structures of the individual ranges, outlining or partially outlining the mountain blocks and (2) the secondary or minor structures superposed on both mountain blocks and basins alike. Chronologically, the initial or early phase of the Laramide deformation produced the major structural features and thus blocked out the mountain ranges. Later more surficial Laramide movements superposed secondary features on the major structures.

The combination of these primary and secondary foreland structures forms a unique and striking tectonic pattern. The axes of the secondary elements are all nearly parallel, having a strike of N. 40°–50° W. This strike is retained regardless of the trend of the ranges or basins of which they are a part, that is, irrespective of the strike of the major structural elements. Thus, for example, although the Beartooth–Absaroka–Owl Creek–Bridger–Bighorn–Pryor uplift forms a huge loop in which the major structural trends swing through 180°, the axes of the secondary elements remain constant at N. 40°–50° W. from one end of the loop to the other. Furthermore, although the secondary features are all approximately parallel and all asymmetrical, they are not all asymmetrical in the same direction. The foreland region seems to be divided into five more or less distinct strips or belts trending roughly northeast-southwest across the entire area, that is, across mountain ranges and basins alike. Within each of these strips the secondary features are all asymmetrical in the same direction (see tectonic map of Bighorn–Beartooth–Wind River area, Fig 4).

#### GEOSYNCLINAL STRUCTURAL TYPES

The structures of the narrow and elongate geosynclinal belt to the southwest of the foreland are in striking contrast to the tectonic features of the platform area. They have developed in response to stresses acting on a region where the sediments had attained great thicknesses (20,000–45,000 feet; see Fig. 3). These structures have been well summarized by Horberg as follows:

Forming a relatively narrow belt, which follows either a northerly or northwesterly direction, the group is made up of a series of parallel structures which persist for long distances. The individual folds are closely compressed and often overturned to the east. Taken together they form a folded system of the Appalachian type. Probably the outstanding feature of the belt is a series of faults which to the north are exemplified by the Lewis, Lombard, and Heart Mountain faults, and farther south by the Darby, Absaroka, Bannock, Willard and Crawford faults. The horizontal displacement along some of these thrusts is probably more than 30 miles. Westward the structures merge with folding of Jurassic age.<sup>9</sup>

At least two other major low-angle thrusts should be added to those of the southern group mentioned by Horberg: (1) the St. John thrust in eastern Idaho<sup>10</sup> and (2) the Jackson thrust, first mapped and described by Horberg.<sup>11</sup>

In addition to the Jackson thrust, whose southwestward continuation into the northern Hoback region has been

<sup>9</sup> *Op. cit.*, p. 25.

<sup>10</sup> The St. John fault was first mapped by A. R. Schultz, "A Geologic Reconnaissance for Phosphate and Coal in Southeastern Idaho and Western Wyoming," *U.S. Geol. Surv. Bull.* 680 (1918), p. 36. The name "St. John" fault was applied by Virgil R. D. Kirkham, "Geology and Oil Possibilities of Bingham, Bonneyville, and Caribou Counties, Idaho," *Idaho Bur. Mines and Geol. Bull.* 8 (1924), pp. 33–34.

<sup>11</sup> *Op. cit.*, pp. 35–36.



mapped by the writers, at least three other low-angle, southwest-dipping thrusts have been encountered in the area mapped, namely, the Game Creek thrust, the Horse Creek thrust, and the Bear Creek thrust. These three thrusts, which lie south or southwest of the Jack-

#### DESCRIPTION OF STRUCTURES FORELAND STRUCTURES

The behavior of blocks typical of the foreland or platform area of the Middle Rocky Mountain province has been discussed by Chamberlin.<sup>12</sup> He noted that in cases where the steep sides of moun-



FIG. 5.—Cache Creek thrust fault between heads of Cache and Horse creeks. Inked line indicates trace of thrust plane in surface. Steep slope above thrust plane made up of (from bottom to top) Mississippian, Devonian, and Ordovician beds. Smooth, gentle slope below thrust plane developed in Upper Cretaceous sediments. Sharp limestone ridge in foreground marks the northern edge of the Jackson thrust sheet near its abrupt eastern termination as shown on the right.

son thrust, are both stratigraphically higher and smaller in extent. Thus the geosynclinal tract represents deformation of the surficial or thin-shelled type occurring where the basement crystallines were buried too deeply beneath weak sediments to be of much influence in shaping the structures, as contrasted to the thick-shelled type of the foreland region.

tain blocks faced a basin the structures varied from simple flexures with high-angle faults to overturned anticlinal limbs and overthrust faults in various stages of development.

The more important structures of the Gros Ventre Range belong to this group; and the characteristic feature of the range is its blocklike pattern, particularly along

<sup>12</sup> *Op. cit.*, pp. 689-90.

the south flank where, throughout most of its extent, the steep mountainside faces Hoback Basin. Previous investigators described the range structurally as involving two parallel, northwest-trending anticlines, with axes about 5 miles apart.<sup>13</sup> The present study indicates that these anticlines are expressions of but two of the four or more foreland-type blocks which, with their related structures, form the basic tectonic pattern of the range. The blocks, three or four of which are distinctive enough to be termed "trap-door" structures,<sup>14</sup> are arranged serially along a N. 50° W. axis and from west to east are successively younger and less intense in degree of deformation. Beginning at the west, these blocks are (a) the Cache Creek thrust block, (b) the Skyline Trail block, (c) the Shoal Creek block with its associated structures, and (d) the Elbow Mountain block. In addition to these, other important structures of similar type, lying slightly to the north of the structural and topographic axis of the range, have been mapped. These include the Jackson Peak fault and the Nowlin Creek anticline.

<sup>13</sup> Orestes St. John, "Report of the Geological Field Work of the Teton Division," *Eleventh Ann. Rept. U.S. Geol. and Geog. Surv. of Territories, Embracing Idaho and Wyoming*, 1879, pp. 448-56.

<sup>14</sup> A descriptive term sometimes applied to a blocklike type of foreland structure, the essential feature of which is a sharply asymmetrical flexure usually broken on its steep flank by a high-angle fault. The flexure or fault or both generally outline two adjacent sides of the block, and displacement is commonly greatest at the corner. The fault surface curves in under the block, and in more advanced stages actually becomes a thrust fault, indicating its ramplike character. Trap doors are thus interpreted as resulting largely from horizontal stresses transmitted through the more competent crystalline complex below the sedimentary cover to pre-existing zones of weakness, where they break up toward or through to the surface to produce a fault having a "sled-runner"-like profile.

#### CACHE CREEK THRUST BLOCK

The dominant tectonic feature of the west end of the Gros Ventre Range is the Cache Creek anticline and the associated Cache Creek thrust fault.

The Cache Creek anticline is a broad, asymmetrical flexure, which can be traced for about 9 miles striking N. 45° to N. 50° W. It is essentially monoclinical in character, having a steep south limb (Figs. 6 and 8, Sec. A-A') which parallels Cache Creek. The dip of the beds on this steep south limb varies from 60° to the south to 50° to the north, where overturn has been strongest. The structure terminates abruptly at the eastern margin of Jackson Hole, either by cross folding of synclinal character or by faulting. Horberg<sup>15</sup> has suggested that the Cache Creek anticline may once have been continuous across Jackson Hole and that its western continuation may be found in the Teton Range as the Taylor Mountain anticline. Eastward the structure loses its distinctiveness and terminates against the Skyline Trail block.

The Cache Creek thrust, representing the broken southwest limb of the Cache Creek anticline, can be traced from the Skyline Trail block westward to Jackson Hole—a distance of approximately 10 miles. Throughout this distance the fault is easily traceable on the north wall of Cache Creek Valley (Fig. 5). Beds exposed on the front of the thrust plate range in age from Jurassic (Twin Creek) to Ordovician (Bighorn), having the steep dips already mentioned in connection with the Cache Creek anticline. These beds have been thrust over Upper Cretaceous (Bear River?) rocks which show strong overturn, dipping 75°-40° N. Nowhere along the trace of the thrust is it possible to observe the fault surface

<sup>15</sup> *Op. cit.*, p. 33.



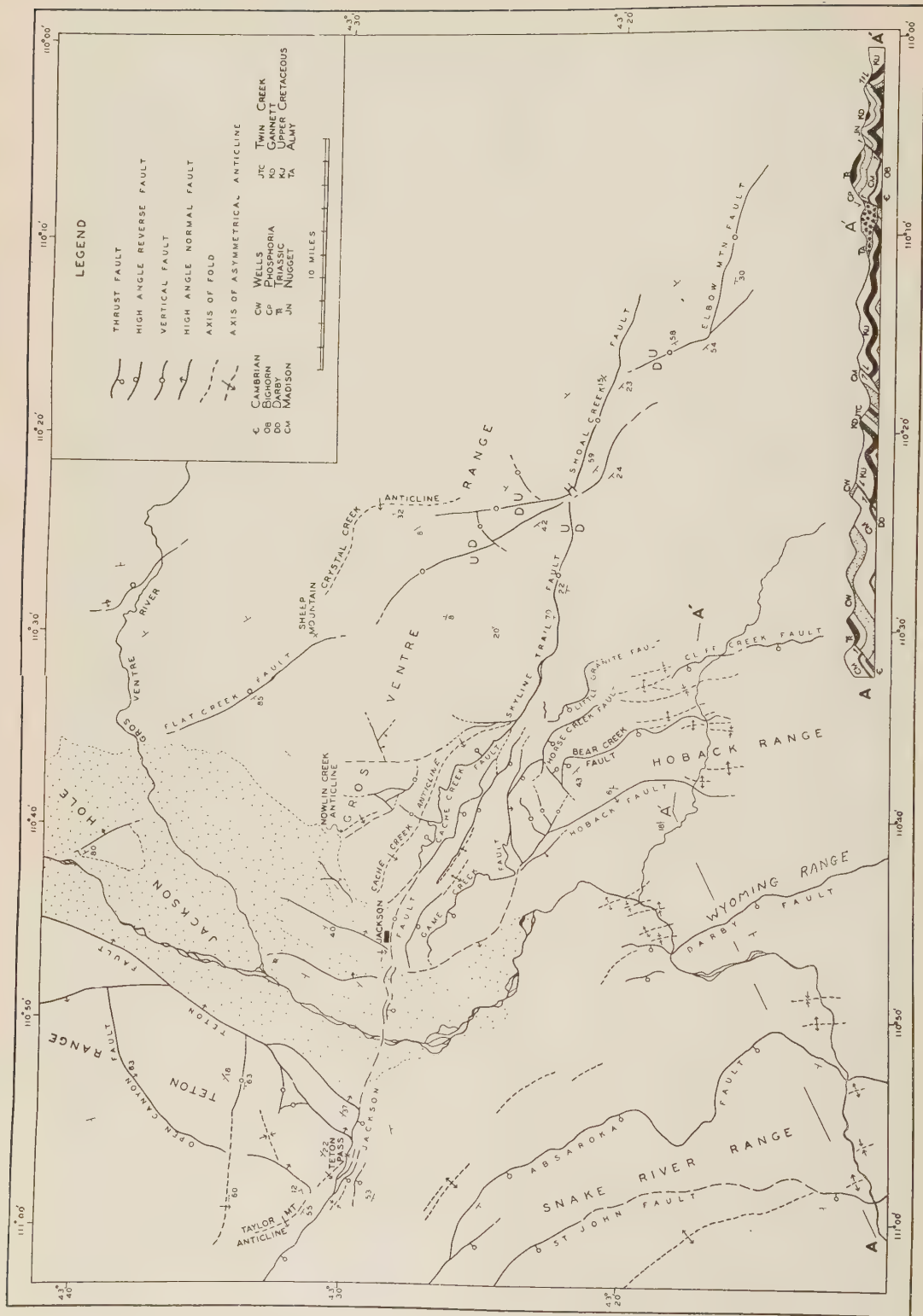


FIG. 6.—Tectonic map of a portion of northwestern Wyoming. (Data compiled by Leland Horberg, Vincent Nelson, and Victor Church)

itself, but its sinuous trace gives ample evidence that it dips to the northeast at an angle of probably no more than  $30^{\circ}$ – $35^{\circ}$ . Horizontal displacement is relatively small, probably nowhere exceeding 1 or  $1\frac{1}{2}$  miles. To the west the fault is covered with the alluvial material of the lower portion of Cache Creek and Jackson Hole, while to the east it terminates against the Skyline Trail fault. Only one small tear fault, having a N.  $30^{\circ}$  E. strike, cuts the Cache Creek thrust. This tear fault produces a small offset in the thrust about 5 miles east of Jackson.

The Cache Creek thrust block, including the Cache Creek anticline, is the earliest formed and most strongly developed of the series of foreland blocks making up the Gros Ventre Range. The forces producing this block were similar to those producing the ramplike trap doors to the east but operated here with such great intensity that accommodation had to be effected by thrusting rather than by high-angle faulting.

#### SKYLINE TRAIL BLOCK

The second of the foreland blocks is outlined by the Skyline Trail fault (Fig. 8, Sec. C–C'), a vertical or high-angle reverse fracture extending for almost 10 miles along a nearly east-west strike before curving to the north near its western end. After turning north it dies out rapidly, disappearing in about 2 miles. At its eastern extremity the structure is cut by the Shoal Creek fault of the third foreland block. Displacement along the fault reaches a maximum at the southwest corner or apex, where the structure swings around to the north. At this point the stratigraphic displacement can be hardly less than 6,000 feet and may be 8,000 feet or more. Precise determination of displacement is not possible, for pre-Cambrian rocks are in apparent con-

tact with the Almy (Tertiary) formation, which was deposited after at least the first phase of the Laramide deformation.

Following the Skyline Trail fault eastward from the apex of the block, displacement diminishes regularly at about 350–400 feet per mile. Just west of its termination against the Shoal Creek fault the Skyline Trail fault has a minimum stratigraphic displacement of about 1,000–1,200 feet (Madison to Dinwoody). Actual displacement may be somewhat greater, however, since both formations are essentially vertical.

North of the fault the Paleozoic beds dip evenly to the northeast at angles ranging from  $10^{\circ}$  to  $20^{\circ}$  (Fig. 9). Near the fault the beds flex over sharply, assuming a high southwest dip or even becoming vertical in some places. The Mesozoic formations in contact with the Paleozoics at the fault generally have similar attitudes, but at some points they are even overturned.

Closely associated with this structure is a high-angle fracture, the Sheep Creek fault (Fig. 7), which branches off on the west side of the north extension of the Skyline Trail fault. For a mile or so it diverges but little from the Skyline Trail fault, but then it swings to the northwest for 1 or 2 miles before returning again to a north-south strike. This structure is of particular interest, since displacement along it increases from almost nothing at its juncture with the Skyline Trail fault to 700 or 800 feet directly east of Jackson Peak and is in reverse relation to that of the Skyline Trail fault, that is, the west side is the upthrow side. This peculiar pattern, suggesting modified pivot or scissors faulting, assumes added significance, since almost identical relations are shown in connection with the Shoal Creek–Pyramid Peak faults to the east.





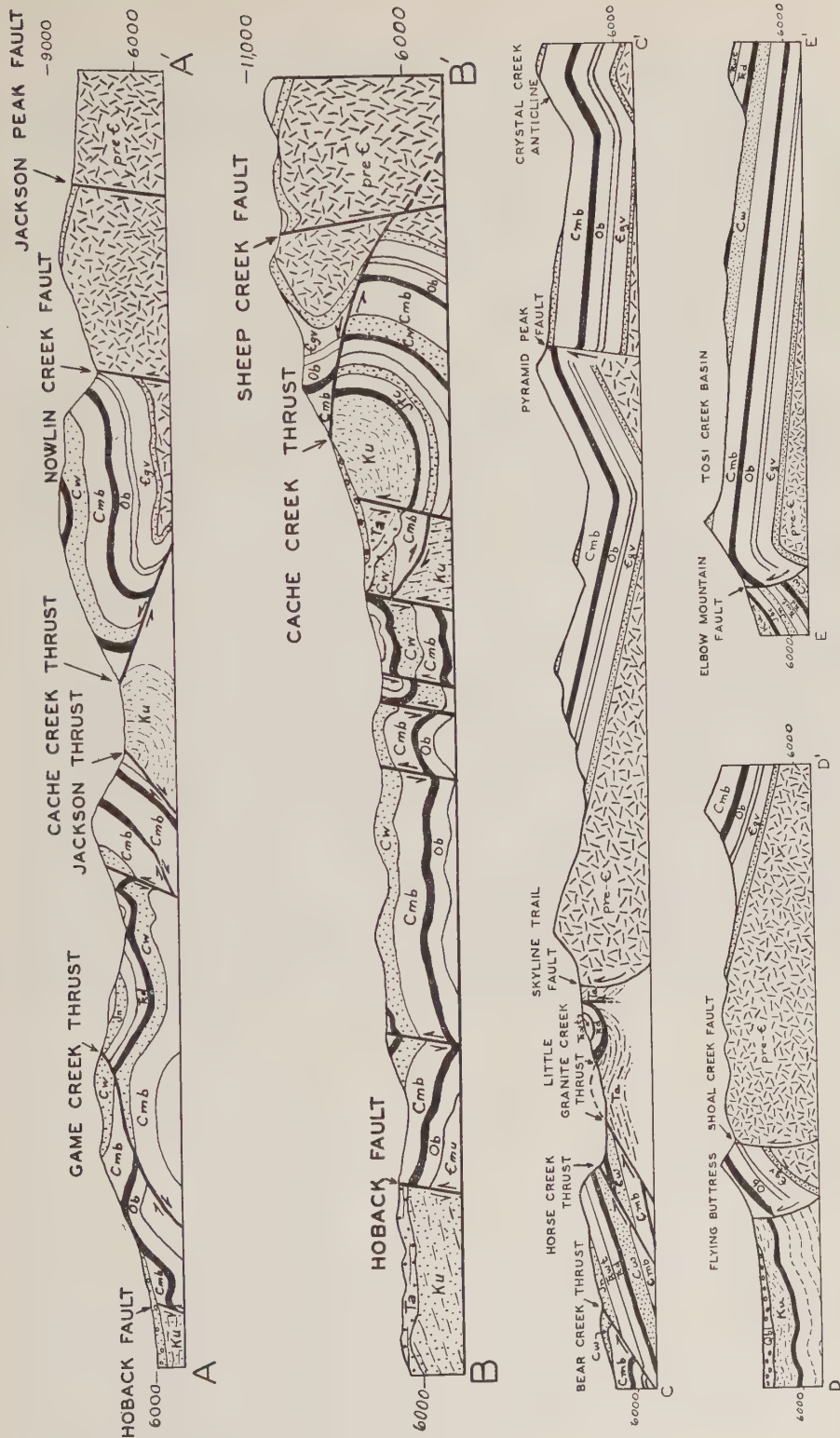


FIG. 8.—Cross-sections of the Gros Ventre-northern Hoback area

SHOAL CREEK BLOCK AND ASSOCIATED  
STRUCTURES

The Skyline Trail structure terminates abruptly against the Shoal Creek fault, a conspicuous fracture which bounds the western and southern sides of the next well-defined trap-door block. It is an essentially vertical or high-angle normal fracture (Fig. 8, Sec. *B-B'*), with an average strike of N.  $75^{\circ}$  W. along the

occurs about  $2\frac{1}{2}$  miles east of the southwest corner, is 2,000–3,000 feet (pre-Cambrian to Wells). At the southwest corner of the block, where a sharp notch (elevation 9,500 feet) has developed between two 11,000-foot peaks, the displacement is only 1,100 feet (lower Flathead to upper Gallatin).

South of the Shoal Creek fault near its western end, and almost detached by



FIG. 9.—Gently dipping Paleozoic beds on north slope of the Skyline Trail block

southern side of the block. The strike swings rapidly to N.  $10^{\circ}$  W. just west of the Shoal–Swift Creek drainage divide and continues northward for about 3 miles before dying out. Along the southern side of the block the fault may be traced for nearly 9 miles, when it gradually disappears within the Madison formation in Tosi Creek Basin. Like the Skyline Trail fault, the displacement is greatest along the southern margin of the block. Maximum displacement, which

it from the rest of the range, is a high, prominent peak (11,100 feet) called the “Flying Buttress” (Fig. 10). The strata on the south side of this tectonically significant peak attain dips of  $65^{\circ}$ – $75^{\circ}$  to the south. On the north side the beds are cut off sharply to form an abrupt massive wall of remarkable linearity. This north face of the Flying Buttress has been developed along the Shoal Creek fault, while on its south and west sides it is outlined by a fault which swings



around in a sweeping arc quite similar to the changes in strike seen along the Skyline Trail, Shoal Creek, and Elbow Mountain faults. Maximum displacement is at least 2,500 feet and may be even more (Madison to Upper Cretaceous). Since this fault has been cut by the Shoal Creek fault, it is evident that it developed during the first phase of the foreland deformation of the Laramide

metrical to the southwest with dips as high as  $35^{\circ}$  on the steep flank. The axial high of the structure lies to the east of the upper part of Crystal Creek. It turns west along the west branch of Crystal Creek before swinging north and dying out on the north flank of the range east of Sheep Mountain.

Near the southwest corner of the Shoal Creek fault a minor vertical fracture—



FIG. 10.—Steeply dipping strata on the south side of the Flying Buttress as viewed from the west

orogeny. The Shoal Creek fault represents a second phase. Thus the Flying Buttress is a nose or slice of the south side of an original trap-door block left behind when the second phase of deformation produced a fault which broke through a little to the north of the original fracture.

The Crystal Creek anticline (Fig. 7) represents the northward continuation of the Shoal Creek structure. The anticline is a broad, open structure, asym-

metrical to the southwest with dips as high as  $35^{\circ}$  on the steep flank. The axial high of the structure lies to the east of the upper part of Crystal Creek. It turns west along the west branch of Crystal Creek before swinging north and dying out on the north flank of the range east of Sheep Mountain. Near the southwest corner of the Shoal Creek fault a minor vertical fracture—

the Pyramid Peak fault (Fig. 7)—developed and strikes northwest across the central part of the range. The displacement is slight near the Shoal Creek fault but increases steadily to the northwest, until at Pyramid Peak it is estimated to be 1,000–1,200 feet. The upthrow side of this fault is on the west, or reversed from that on the Shoal Creek fault. Thus the relations are strikingly similar to those existing between the Sheep Creek and the Skyline Trail faults, indicating that

both the Pyramid Peak and the Sheep Creek faults are closely related in origin.

#### ELBOW MOUNTAIN BLOCK

South and east of the Shoal Creek block lies the block outlined by the Elbow Mountain fault (Fig. 8, Sec. *E-E'*). The name for this fault, derived from the prominent mass forming most of the southeast portion of the Gros Ventre Range, is singularly descriptive of the structural, as well as the topographic, features of the block. Elbow Mountain is an elevated mass of Paleozoic sediments, cut off on the south and west to form a bold escarpment. The bordering fault of this block can be traced for 5 miles along the south side and 3 miles along the west side of Elbow Mountain. Its strike is more regular than that of the Cache Creek thrust, Skyline Trail, or Shoal Creek faults, and averages N. 80° W. on the south side and N. 30° W. on the west. The displacement, considerably less than along any of the previously discussed major block structures, reaches a maximum at the southwest corner, where it is about 2,500 feet (Bighorn to Twin Creek). The amount of movement on the fault diminishes along the strike both to the north and to the east, and the fault dies out in the Wells formation at both extremities. To the north there is no folding to represent the continuation of the structure, but to the east a monoclinical flexure along Rock Creek apparently continues the displacement in decreasing amount to the east end of the range.

A fault of minor importance—the Jack Creek fault—branches from the Elbow Mountain fault at the corner of the block and strikes southeast. Displacement is moderate (1,000 feet or less) near Elbow Mountain and diminishes southeast. South of Jack Creek the fault

is lost under the cover of Tertiary conglomerate.

#### JACKSON PEAK FAULT

This structure is a high-angle or vertical fault which outlines the south and west sides of the pre-Cambrian block, dominated by Jackson Peak in the northwest portion of the range (Fig. 7). The Jackson Peak fault terminates either by intersection with the Sheep Creek fault about  $\frac{3}{4}$  mile southeast of Jackson Peak or dies out very rapidly within the outcrop area of pre-Cambrian rocks in that vicinity. From its eastern extremity the fault strikes westward for approximately 1 mile and then curves sharply to the north, following the drainage line of a small stream to the northern boundary of the mapped area. Maximum displacement along the structure occurs at its southwest corner (pre-Cambrian to Gros Ventre) and is difficult to determine but is estimated at no less than 2,200 feet and it may be even more. The block thus outlined by the Jackson Peak fault resembles closely the typical foreland-type blocks to the east and probably should be regarded as a trap-door block.

#### NOWLIN CREEK ANTICLINE

This structure lies about 3–4 miles north of and parallel to the Cache Creek anticline (Fig. 6), which it resembles in many respects. It is asymmetrical to the southwest, terminates abruptly to the west at Jackson Hole, and disappears to the east near the Skyline Trail block. Here the Nowlin Creek and Cache Creek flexures apparently merge. Horberg<sup>16</sup> has suggested that the Nowlin Creek anticline may continue westward across Jackson Hole and reappear in the Teton Range as the Moose Creek anticline.

<sup>16</sup> *Ibid.*

## GEOSYNCLINAL STRUCTURES

## THRUST FAULTS OF THE GEOSYNCLINAL BELT

*The Jackson and Little Granite thrusts.*—In the western portion of the area under consideration the northern margin of the geosynclinal tract is marked by the southwest-dipping Jackson thrust, which was first mapped by Horberg.<sup>17</sup> In his area the fault may be seen emerging from the Tertiary lava cover just a little east of Victor, Idaho, thence continues east through Teton Pass across Jackson Hole and into the northern edge of the Hoback Range. Here it may be traced southeast from the east margin of Jackson Hole for a distance of about  $8\frac{1}{2}$  miles (Fig. 7), having an average strike of about S.  $60^{\circ}$  E. The thrust follows along the south wall of Cache Creek Valley, giving Cache Creek a remarkable structural setting, since it occupies a position between two thrusts, the northeast-dipping Cache Creek thrust on the north and the southwest-dipping Jackson thrust on the south (Fig. 8, Sec. A-A').

Nowhere along its trace is the plane of the Jackson thrust exposed; but, judging from the course of the fault, the plane must dip at a relatively low angle to the southwest. Along most of the fault, stratigraphic relations show nearly vertical Carboniferous (Madison ls.) resting on Upper Cretaceous beds. However, at one exposure approximately 4 miles up from the mouth of Cache Creek Valley, Upper Cambrian beds were observed at the front of the thrust sheet, suggesting that the thrust mass may possibly have ridden on Middle Cambrian shales.

Some faulting of the imbricate type is unquestionably associated with the Jackson fault. The Madison limestone found at the front of the thrust sheet is far too thick to represent normal relation-

ships. Poor exposures on the entire north-facing slope of Cache Creek Valley made it difficult to trace such slice faults, but evidence of such faulting was found at one place where the Darby limestone occurs between outcrops of almost vertical Mississippian (Madison) limestone. Though the exact course of this minor fault could not be traced for any distance, such a fault has been indicated on the map (Fig. 7), and it is quite possible that several other small slices are present within the Madison limestone.

The Jackson thrust sheet terminates abruptly as a nose of vertical Madison limestone in contact with Almy (Eocene?) conglomerate about  $8\frac{1}{2}$  miles southeast of Jackson Hole.

About  $3\frac{1}{4}$  miles southeast of the eastern termination of the Jackson thrust a second thrust mass from the southwest is encountered. This has been called the "Little Granite" thrust, from exposures along the creek of that name. The Little Granite thrust is exposed first in the eastern part of the Horse Creek drainage area (Fig. 7), crosses the Horse Creek-Little Granite drainage divide, and continues east for a short distance along the southern side of the upper part of Little Granite Creek before swinging south and dying out in a fold. The general relations along the fault show late Paleozoic and early Mesozoic beds thrust over Cretaceous formations, but in one exposure in a small basin-shaped valley near the western extremity of the thrust extremely significant relations are shown (Fig. 8, Sec. C-C'). Here late Paleozoics, making up a portion of the thrust sheet, are resting on the Almy conglomerate of early Tertiary age. The exposure of the Almy below the thrust sheet is a window in the overriding block, for the thrust relations seen on the south side of the basin are repeated on the north side  $\frac{3}{4}$ -1 mile

<sup>17</sup> *Ibid.*, p. 35.



away. Patches of till on both the east and the west sides make it impossible to trace completely the outline of the window. The fault plane on the north side of the window dips to the north or in the opposite direction from the normal dip of the fault. This change in dip seems to be due to later faulting and associated folding which affected the region sometime after the major Laramide deformation.

Mention has already been made of the sudden termination of the Jackson fault at its southeast end and the difficulties encountered in attempting to trace the Little Granite thrust westward from the window of Almy because of glacial-drift cover. There are then two possible interpretations for the relations between these faults: (1) they are two separate thrusts; (2) they are one continuous thrust.

At the east end of the Jackson thrust vertical beds of Madison limestone are in contact with the Almy conglomerate (Eocene?). Just a little west of this point the Almy occurs at higher elevations than the thrust plate and also covers small portions of its front. Thus in this area the age of the Almy is post-thrusting. No doubt the material composing the Almy conglomerate came from the area of the high Gros Ventres lying to the north, where the Mesozoic beds have been stripped away. In many places the material of the Almy is extremely coarse, so that originally the formation must have had a moderate initial dip to the south; but the Almy, as it now lies adjacent to and east of the Jackson thrust, dips steeply to the north ( $45^\circ$ ). Traced eastward, the formation gradually flattens out and finally retains only the original south dip.

A normal fault lies a short distance south of and roughly parallel to the Jackson thrust fault but continues

southeastward beyond the easternmost exposure of the Jackson thrust. The reversal of dip of the Almy conglomerate directly east of the termination of the Jackson thrust has led the writers to suspect a second high-angle, arcuate, hinge-like fault that branches from the first-mentioned fault and strikes N.  $65^\circ$  E. to east-west. This fault cut across the Jackson thrust sheet and the overlying Almy, producing a hinge block between it and the normal fault to the south. The north side of this hinge block was dropped, burying the southeastern part of the Jackson thrust sheet and tilting the Almy to the northeast (Fig. 8, Sec. B-B'). Since the fault dies out to the east, as indicated by the gradual flattening of the Almy, the Jackson fault may reappear at the surface farther on as the Little Granite thrust. If the Jackson and the Little Granite thrusts are one and the same, it is necessary to assume that there was renewed movement on the southeastern portion of the thrust in post-Almy time, since the Almy is exposed in the window at the western end of the Little Granite fault. Despite the rather specific set of conditions required by the hypothesis that the Jackson and Little Granite thrusts are one single fault, the writers favor this hypothesis for the following reasons: (1) the two faults are separated from each other by a distance of less than 3 miles; (2) the faults are striking in directions which should bring them together; and (3) they are the outermost thrusts in a relatively wide zone of thrusting.

*The Game Creek thrust.*—In the western portion of the area the front of a second thrust sheet is encountered about  $2\frac{1}{2}$  miles southwest of the Jackson fault (Fig. 8, Sec. A-A'). It has been called the "Game Creek" thrust, for the plane of the fault is well exposed on the valley

sides of Game Creek, which forms a large re-entrant in the thrust sheet. Exposures in the valley are especially striking, since the gray Mississippian limestone has been thrust over the brilliant red and brown Triassic formations.

The Game Creek thrust may be traced from the eastern margin of Jackson Hole to the southeast for approximately 7 miles. Its trace roughly parallels the strike of the Jackson thrust. The front portion of the thrust plate is made up of Carboniferous beds which have been thrust over closely folded Triassic and Jurassic beds. From the exposures of the fault surface on the sides of Game Creek Valley it may be seen that the thrust plane is essentially horizontal for a distance of about 1 mile southwest from its front, but then it dips steeply to the southwest as a result of drag on a normal fault which cuts the thrust plate. South of this normal fault the plane of the thrust lies below the surface.

High-angle faulting has made it impossible to trace the Game Creek fault for more than the 7 miles already specified. The western margin of the Hoback Range is outlined by a high-angle fault (the Hoback fault), having its downthrow side to the west. At the northwest end of the range this fault produces truncation of all the northwest-trending structures, including the Game Creek fault, at the east margin of Jackson Hole. In following the trace of the Game Creek plane southeastward, one loses it on the divide between Game and Porcupine creeks. Here the thrust is again cut by a high-angle fault which strikes nearly east-west and has its downthrow side to the south, with the consequent dropping of the thrust plane below the surface.

*The Horse Creek thrust.*—The thrust relationships of this fault are clearly shown just a little east of the junction of

the two main branches of Horse Creek. Here the plane of the fault is exposed at creek level, with nearly flat-lying Madison limestone resting on almost vertically standing beds of late Paleozoic and early Mesozoic age, which strike at nearly right angles to the trace of the fault plane. Traced to the east, southeast, and south, the fault follows closely the east branch of Horse Creek (Fig. 8, Sec. C-C') before swinging south near the head of the creek. Along this course it cuts higher both topographically and stratigraphically. In all, the fault may be traced for a distance of about 4 miles. To the south it terminates in a fold within the Nugget formation, while westward the stratigraphic displacement decreases from the maximum of Madison over Woodside-Thaynes, near the head of the creek, to Madison over Wells and then dies out within the Wells between Horse and Porcupine creeks.

*The Bear Creek and Cliff Creek thrusts.*—Two other thrusts in the northern end of the Hoback Range have been traced by Horberg, who extended the writers' mapping southward across Hoback Canyon. The northern end of one of these—the Bear Creek thrust—is shown on the map (Fig. 8, Sec. C-C'). It follows the east border of the main crest of the range, trending N. 20° W., and, unlike the other structures, does not reflect the change of trend from north-south to northwest at the northern end of the range. The fault is clearly related to folding and appears to represent a broad anticlinal structure thrust eastward over a compressed syncline. Stratigraphic displacement is at no point over 1,000 feet. Northward the fault plane flattens and disappears along bedding planes in the Wells formation. The structure has been traced south to the Hoback River, where the displacement

is small, and normal fold relations appear to exist to the south.

Although only the northernmost end of the Cliff Creek thrust is within the map limits, its relation to the general tectonic pattern (see Fig. 6) is so important that it should be described briefly. The Cliff Creek thrust marks the eastern border of the Hoback Range. Along most of the thrust front the Nugget sandstone is in contact with the Evanston (Fort Union) formation, in which Hoback Basin to the east has been eroded. The outer margin of the thrust mass is represented by discontinuous monoclinical ridges and isolated noses developed along the strike of the Nugget sandstone. The northernmost hogback is found immediately east of the mouth of Little Granite Creek, and from this point similar features continue south as conspicuous land forms for a distance of 18 miles.<sup>18</sup> North of the northernmost hogback the fault dies out rapidly in a sharp fold. Although the Evanston beds east of the fault have been sharply folded in places, the Cliff Creek fault may properly be considered the eastern border of the geosynclinal deformation.

*Relationships of the thrusts.*—A notable feature of those ranges within the geosynclinal tract (the Hoback and Snake River ranges in particular) is the sharp swing in the strike of their main structures where they abut the foreland region (Gros Ventres and Tetons). Throughout most of the Hoback Range the structures trend north-south, but at its northern end they curve sharply to the northwest. The Cliff Creek fault, marking the eastern boundary of the range through most of its course, dies out at the northeast corner of the range. Here, at the point of curvature between the

northern and eastern boundaries of the Hoback Mountains, there is a series of small, discontinuous thrusts taking the place of a single boundary structure. These thrusts have served to take up the stresses by slicing around the Gros Ventre buttress. Nearly all these small thrusts have northwest strikes at their northern ends and curve to the southeast and south at their opposite ends. Westward from the strong arc between the eastern and northern boundaries of the range, a single continuous fault (the Jackson thrust) again forms the main boundary structure of the geosynclinal region in both the western portion of the map area and the Teton area across Jackson Hole to the west. Of the several thrusts described, perhaps only the Jackson and the Cliff Creek structures should be considered major features. The other faults (i.e., the Bear Creek, Game Creek, Horse Creek, and perhaps the Little Granite, if it is not a part of the Jackson fault, as here supposed) collectively make up the continuation of the thrust zone represented by the Jackson fault on the northern, and the Cliff Creek fault on the eastern, boundaries of the curving geosynclinal tract.

*Folding associated with the thrust faulting.*—Prior to the development of the numerous thrust faults in the geosynclinal tract the rocks underwent severe deformation by folding. The stresses responsible for this folding were so great and the deformation progressed so far that finally the rocks were forced to yield by thrusting. That much of the tight folding preceded the major thrusting can be seen upon examination of the beds lying below the thrust planes. In many places the Triassic and Jurassic formations particularly have been thrown into a series of folds too close and numerous to be plotted on the map. Not un-

<sup>18</sup> See Gros Ventre Quadrangle, Wyoming, topographic map.



commonly, folding is localized within a single formation, and in several places chevron folds have developed on a comparatively large scale.

#### HIGH-ANGLE FAULTING

Several high-angle normal faults of Tertiary age are found in the northern Hoback Range. The most important of these is the Hoback fault (Figs. 6 and 7), which outlines the western margin of the Hoback Range. This fault has been accurately traced from a point about a mile south of Hoback Canyon to Game Creek. North of Game Creek the fault itself cannot be seen, but there is ample evidence to indicate its presence along the base of the range. The west-facing slope of the range has the appearance of a scarp, and, beyond the front of the Game Creek thrust sheet, nearly vertical west- and northwest-striking beds terminate abruptly to form the east rim of Jackson Hole. These same beds with similar strike reappear a short distance to the west in the small "butte" southwest of Jackson, indicating that they were faulted out of the intervening area. Relations along the Hoback fault between Game Creek and the ridge separating Porcupine and Horse creeks show Nugget resting against Wells. South of this the Almy conglomerate lies on the downthrow side adjacent to Paleozoic and Mesozoic beds.

Several faults of minor importance, having predominantly northeast strikes and terminating against the Hoback fault, lie in the area between Game and Horse creeks. One of these is the fault which cuts off the southeastern extension of the Game Creek thrust. This fault can be traced from its intersection with the Hoback fault to a point about 6 miles to the east before dying out in the Upper Woodside-Thaynes.

A relatively long normal fault lies a short distance south of and roughly parallel to the Jackson fault. It continues eastward beyond the easternmost exposure of the Jackson fault and in so doing has dropped the Phosphoria formation (a part of the Jackson thrust sheet) against the northeast-dipping Almy conglomerate, which here covers the front portion of the thrust mass.

#### DEVELOPMENT OF STRUCTURES

The descriptions of structures have shown that there are marked differences in the tectonic patterns of the geosynclinal and foreland tracts, but the sequence of development of these types must still be considered.

#### PRE-LARAMIDE DIASTROPHISM

The only pre-Laramide diastrophism of any importance to affect the area occurred in pre-Cambrian time. The crystalline rocks indicate long periods of sedimentation, folding, igneous activity, and erosion prior to the deposition of the Middle Cambrian sands. This pre-Laramide diastrophism is of importance in understanding the present structures, for it is believed that the structural trends and lines of weakness developed then were effective in determining the tectonic pattern assumed in the foreland area during the Laramide revolution.

#### DEVELOPMENT OF LARAMIDE STRUCTURES

The Laramide orogeny, which was responsible for the development of the open asymmetrical folds and trap-door structures of the Gros Ventre area, as well as the close folds and associated thrust faults of the Hoback region, began after the deposition of the Frontier formation. From evidence available within the Gros Ventre-Hoback area, the dating of the close of this period of deformation

presents somewhat more of a problem. Field evidence, such as that presented in the discussion of the trap-door blocks and Jackson thrust, indicates that most of the movement preceded the deposition of the Almy. However, some post-Almy movement is indicated in the Little Granite thrust, as well as on the Skyline Trail and Shoal Creek faults. It is not possible with the evidence available within the area to date this post-Almy movement, but it is considered of secondary importance and not the main episode of the Laramide deformation. The age of the Almy has not been fixed definitely; but beds of the Evanston formation, which lie stratigraphically below the Almy, have been sharply folded east of the Hoback Range in Hoback Canyon. The Evanston is thought to be the equivalent of the Fort Union, indicating that the deformation continued well into Paleocene time.

Thus the deformation responsible for the foreland and geosynclinal structures extended over a considerable period of time, and it seems likely that the two types of structures may not have developed simultaneously. The surficial movement produced in the geosynclinal and foreland areas by the causal forces was in opposite directions. This is evident from examination of nearly all the structures found in the two areas. In the foreland tract virtually all the major structures are asymmetrical to the southwest. The major folds, that is, the Cache Creek anticline, Nowlin Creek anticline, etc., have their steep limbs to the southwest. Thrusting on the Cache Creek thrust has been from the northeast; and the trap-door blocks have been interpreted as ramp structures, indicating some active horizontal stress from the northeast. In the geosynclinal area all the thrust-fault planes dip southwest or

south with overriding toward the east and northeast.

It is possible that the Laramide stresses may have produced the surficial movements in opposite directions simultaneously, but a more likely interpretation would be that the causal forces produced surficial movement in the one area as long as that area could give the required crustal shortening most easily. Later the deformation could shift to the adjoining area, producing surficial movement which might very well be in an opposite direction. Evidence of such two-phase deformation is to be found in the area of the Jackson and Cache Creek thrusts. It seems reasonable to believe that the fronts of both the Jackson and the Cache Creek thrust masses have been stripped back by erosion considerable distances from their original positions. This means that, if the two thrusts developed simultaneously, their overlap would have been much greater than if one had developed earlier than the other and probably great enough that some remnants of the overlap should be found, but they are entirely absent.

To determine in which region the deformation was earlier, direct data must be sought outside the Gros Ventre-Hoback area. The Cache Creek anticline of the foreland area probably has its continuation in the Taylor Mountain anticline of the Teton Pass area.<sup>19</sup> Horberg<sup>20</sup> has found in that area that the Jackson thrust of the geosyncline partially covers the south limb of the anticline and that the foot-wall block of the Jackson fault west of Teton Pass is made up of beds ranging in age from Nugget to Upper Cretaceous, indicating considerable erosion of the Taylor Mountain fold

<sup>19</sup> Horberg, *op. cit.*, p. 33.

<sup>20</sup> *Ibid.*, pp. 35-36.

prior to thrusting. From this evidence it seems reasonably certain that the foreland structures developed somewhat earlier than the geosynclinal structures. This order of events seems quite logical also, inasmuch as the structures of the foreland area probably developed along earlier lines of weakness in the pre-Cambrian complex.

With the foreland structures developing first, they would serve as buttresses against which the geosynclinal structures might be pushed. Evidence of this buttressing effect is seen in the abrupt change of strike assumed by the outermost of the geosynclinal structures where they impinge on the south ends of the Gros Ventre and Teton ranges. The major structures of the Hoback Range trend essentially north-south until they approach the south end of the Gros Ventres, where they suddenly swing to the northwest around the buttress. In the same way the structures of the Snake River Range change from a north-south strike to a northwest strike where they meet the Teton structures. Further evidence of this buttressing effect is found in the numerous discontinuous thrusts developed at the northeast end of the Hobacks, where slicing occurred around the buttress.

In summarizing the Laramide diastrophism, the following series of events is indicated. Deformation may have started in the geosynclinal tract with downward movement, but such movement would not have to produce surficial structures to be seen in the field at the present. The earliest recognized deformation occurred in the foreland region. This movement developed the blocklike pattern so characteristic of the foreland region. It was first manifested at the surface by the formation of the asymmetrical anticlines. With continued stress

these anticlines fractured and passed into well-developed trap-door blocks of ramp character. Within the Gros Ventre Range the maximum deformation occurred at the western end, as shown by the series of trap-door blocks becoming progressively stronger to the west; and it seems likely that the Cache Creek thrust fault is simply a trap-door structure in advanced stage of development, exposing the thrust-fault portion of the fracture.

The forces responsible for these structures were manifested largely in vertical movements, although some horizontal yielding is indicated. Somewhat later the deformation shifted to the geosynclinal area. Here the forces were most effective in the sediments themselves, producing shearing over the basement complex and crumpling the overlying strata into a series of close, tight folds. When the rocks could no longer yield sufficiently by folding, thrusting became dominant, forming the numerous thrust masses. It should be noted, however, that the sequence of events as here outlined applies to the border zone between the geosynclinal and foreland areas, making it quite possible for the earliest deformation in the central part of the geosynclinal tract to have started much earlier and even been simultaneous with the yielding in the foreland area. But, by the time the deformation had spread out to the margins of the geosyncline, the foreland area had become relatively stable. This would explain the lapse of time indicated between geosynclinal and foreland deformation within the area studied for this report. After this two-phase period of deformation, the foreland portion of the area (the Gros Ventres) apparently stood high, for detrital material (the Almy conglomerate) derived from it was deposited on the bordering structures of the geosynclinal tract.



Following the deposition of the Almy conglomerate the Laramide deformation came to a close with local renewal of thrusting on the Little Granite thrust, together with renewed movement on the previously outlined trap-door blocks.

#### TERTIARY FAULTING

A period of deformation, following at least the major phases of the Laramide orogeny, is recorded in the numerous high-angle faults which cut across the thrust sheets of the geosynclinal region. From evidence available within the area it is impossible to date these faults more definitely than to say that they are post-thrusting and, most of them, at least, post-Almy. The most important of these faults is the Hoback fault, which outlines the western border of the Hoback Range.

Relationships in the Teton Range show that during early Tertiary time Laramide structures were eroded to a surface of low relief, which was locally covered with volcanic materials, and that in early Miocene time a series of high-angle faults developed.<sup>21</sup> It is faulting of this later period which outlined and tilted the main Teton fault block. It seems logical that faulting of such magnitude

near at hand should also be recorded in the mountainous area on the opposite side of Jackson Hole. Consequently, it is believed that the high-angle faulting of the Hoback area, which has a similar trend, developed at the same time and had its origin in the same forces as those responsible for the Tertiary faulting on the west side of Jackson Hole.

#### EPEIROGENIC MOVEMENTS

The latest stages in the diastrophic history of the area are represented by widespread epeirogenic movements which caused stream rejuvenation and led to the carving of the present mountainous topography. These movements probably began late in the Pliocene and have continued intermittently to the present.

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<sup>21</sup> F. M. Fryxell and Leland Horberg, personal communication.









